Air Quality and Societal Impacts from Predicted Climate Change in Auckland

Nick Talbot

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RIMU Research and Evaluation Unit

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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Climate Change Risk Assessment series 2019

Climate Change Risk Assessment 2019

As communities across the world set out to plan for climate change mitigation and adaptation, they first seek to understand how climate change will affect their city, region, or country.

The Climate Change Risk Assessment (CCRA) has been produced by Auckland Council's Research and Evaluation Unit (RIMU) in support of the Auckland Climate Action Plan (ACAP), at the request of the Chief Sustainability Office. Its aim is to provide information about the risk and vulnerabilities the Auckland region may face under a changing climate regime, which is already underway. In 2018, national climate change projections were scaled-down to produce a more specific picture of their likely effects within the Auckland region. Based on this, CCRA adopted the Intergovernmental Panel on Climate Change's (IPCC) representative concentration pathway (RCP) 8.5 ("business as usual") scenario as its guiding projection, given the lack of evidence of any meaningful and sustained decreases in emissions that would shift to other projection pathways.

The eight reports in the CCRA consider various components of key risks – that is, hazard, exposure, and vulnerability – across sectors and systems of interest: people (heat vulnerability, climate change and air quality), society (social vulnerability and flooding), and natural environment (terrestrial and marine ecosystems), as well sea level rise at regional and local scales. A summary report has also been produced.

Titles in the Climate Change Risk Assessment series:

An assessment of vulnerability to climate change in Auckland
Fernandez, M. A. and N. E. Golubiewski (2019)

Development of the Auckland Heat Vulnerability Index
Joynt, J. L. R. and N. E. Golubiewski (2019)

Air quality and societal impacts from predicted climate change in Auckland
Talbot, N. (2019)

Climate change risk assessment for terrestrial species and ecosystems in the Auckland region
Bishop, C. D. and T. J. Landers (2019)

Climate change risk assessment for Auckland's marine and freshwater ecosystems
Foley, M. M. and M. Carbines (2019)

Flooding risk in a changing climate
Golubiewski, N. E., J. L. R. Joynt and K. Balderston (2019)

Auckland's exposure to sea level rise: Part 1 – Regional inventory
Golubiewski, N. E., K. Balderston, C. Hu and J. Boyle (2019)

Auckland's exposure to sea level rise: Part 2 – Local inventory (forthcoming)
Boyle, J., N. E. Golubiewski, K. Balderston and C. Hu (2019)

Summary: *Climate change risks in Auckland*
Auckland Council (2019). Prepared by Arup for Auckland Council

Executive summary

Emissions from human activities released into the atmosphere act to change its composition. This can be observed globally through climate change, and locally with degraded air quality. Although often considered separately, climate change and air quality have many common attributes that together, deliver complex environmental challenges. The global scale of climate change and the more regionalised scale of air pollution have encouraged holistic policies that “think global, act local” in their approach.

A climate report recently released by the National Institute of Water and Atmospheric Research (NIWA) models possible climate outcomes for Auckland under different emission scenarios (Pearce et al., 2018). The results reported in this report could assist the council in the development of targeted climate mitigation and vulnerability strategies.

The principal findings from NIWA’s climate change report are evaluated in the context of possible air quality implications for Auckland. National and international research offers evidence of how climate change scenarios may have both positive and adverse effects on air quality. Negative effects are driven by prospective increases in tropospheric ozone concentrations, lower dispersion and deposition of particulates and increased aeroallergen contributions. Conversely, air quality could improve by lowering wood burning emissions from domestic heating and increased wet deposition through increased atmospheric water vapour.

Climate-enhanced air pollution can impact certain communities due to existing social and landscape issues. A review of current knowledge of these factors is discussed.

The evidence provided in this report could provide guidance for the development of mitigation and adaptive strategies at local and regional governance levels.

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1. Introduction

New Zealand's climate is changing. The summer of 2018 has produced the warmest weather on record for the north of New Zealand, after the 2017 winter that recorded national temperatures well above the long-term average along with anomalous heavy rainfall events that caused severe disruption to affected regions (Brandolino, 2018). Such short-term extreme meteorological events are becoming more common in New Zealand (Ministry for the Environment, 2018) and follow a predictable longer-term trend that is representative of a steadily warming atmosphere (Jhun et al., 2015).

As a tool to help Auckland prepare for increasing occurrences of these extreme meteorological events and other climate change related outcomes, Auckland Council commissioned the National Institute of Water and Atmospheric Research (NIWA) to provide a climate projection and impacts report. Future climate scenarios were considered using four representative concentration pathways. Each of these pathways provided a concentration value calculated from the predicted radiative forcing on the atmosphere (Pearce et al., 2018). Within the NIWA report, the relationship between the predicted changes in Auckland's climate and possible implications for the quality of Auckland's air are discussed in broad terms (Pearce et al., 2018).

Any alteration to Auckland's air quality resulting from climate change depends on the rate and significance of changes to the climate and how such climate outcomes may impact upon concentrations of primary and secondary air pollutants (Orru, Ebi, and Forsberg, 2017). The interrelated nature of climate and air quality is a complex physiochemical process with inherent uncertainties embedded in any predictions.

Current research shows that air pollutant concentrations and composition are already responding to changes to the global climate. Tropospheric ozone (O_3) (Fuzzi et al., 2015) black carbon (Carslaw et al., 2010), and fine particulate ($PM_{2.5}$) concentrations (Jacob and Winner, 2009) have shown a response to changing climatic conditions world-wide. Such results have largely been observed using global models rather than local or regional observations. However, more localised investigations support these findings. In America, Jhun et al., (2015) report a correlation between increasing O_3 and $PM_{2.5}$ with increasing temperature whilst Kwak et al., (2017) found that in changes in rainfall intensity and occurrence in Seoul influence NO_2 and $PM_{2.5}$ concentrations. Until now, there has been little investigation into how changes to climate may enhance or decrease air pollution in Auckland.

Auckland Council recognises that some climate change impacts are inevitable (Auckland Council, 2018). Therefore, the ability for communities and stakeholders to adapt for these changes is important from a public policy, social wellbeing and security perspective (Figure 1). These social and landscape factors all have independent and interrelated impacts.

Future research could identify communities which could be more susceptible to climate enhanced air pollutants. This report provides a starting point for local government, community groups and iwi to identify priority areas where monitoring, mitigation and support networks could be implemented.

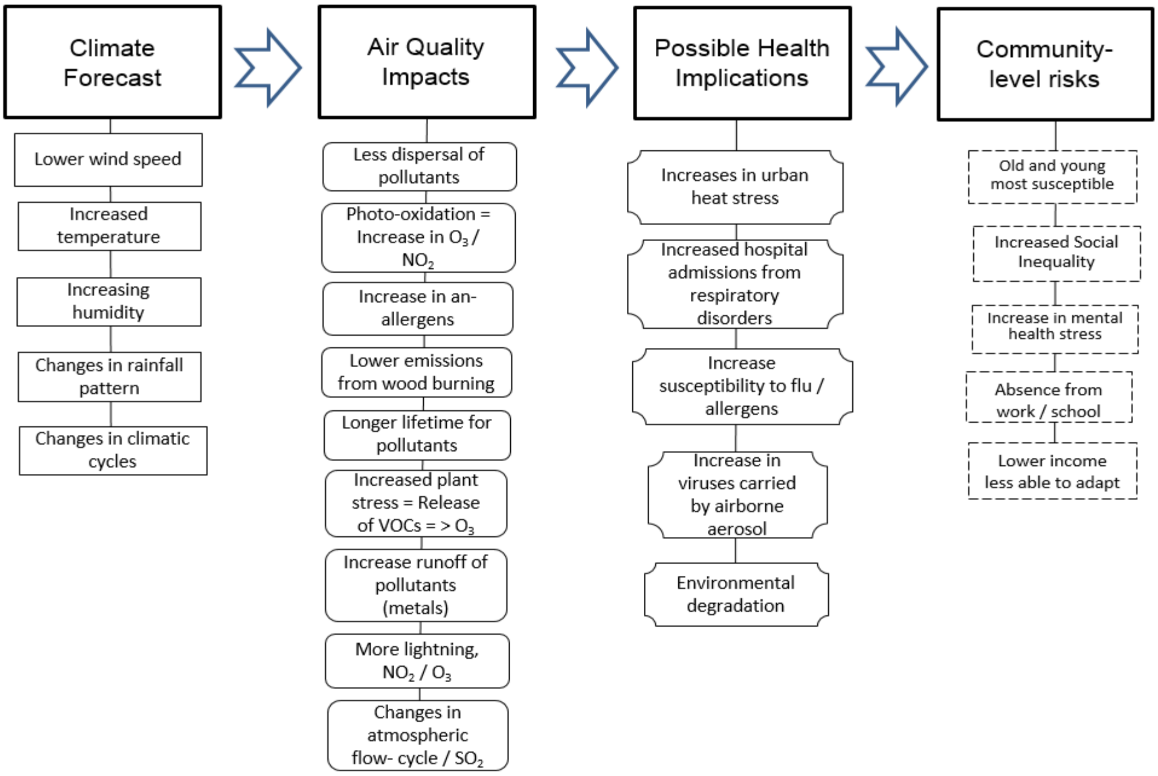

Figure 1 Flow and attributes chart showing the major impacts of climate change and the likely interrelated resultant air quality, health and socio-demographic effects. The chart shows the four key climate parameters and possible air quality outcomes.

2. Potential air quality effects from climate change across Auckland

Meteorological conditions are known to influence air quality. A prominent example is the wintertime formation of brown haze across Auckland's skyline which has been found to be strongly meteorologically dependent (Salmond et al., 2016). Moreover, many airborne constituents including aeroallergens (D'Amato et al., 2015), particulate and gas concentrations (Cheng and Lam, 1998), and black carbon (Crimmins, 2017) have all demonstrated the importance of meteorology.

The association between air quality and climate change is discussed using findings from national and international literature where such impacts are already being identified. Reported results are then extrapolated and discussed within an Auckland context of possible climate change induced impacts.

Throughout this report, NIWA's climate projections for RCP 8.5 'business as usual' scenario is used. This "worst-case" scenario allows exploration of the possible impacts on air quality and societal wellbeing across Auckland if climate change is not mitigated.

The meaning of the different RCP scenarios is explained in full within the NIWA report (Pearce et al., 2018).

2.1. Temperature and solar radiation

This section describes how temperature and solar radiation influences air pollution levels across urban areas such as Auckland. Climate change will influence the temperature profile and alter solar radiation (Section 2.1.1). These changes are then considered in relation to air quality impacts derived from national and international literature (Section 2.1.2).

2.1.1. Temperature and solar radiation climate predictions from NIWA

Summary of predicted changes:

- The whole of the Auckland region is forecast to experience significant warming over the next century.
- Auckland is predicted to experience between 30 and 70 more hot days per year (days over 25°C).
- The number of cold nights/frosts (<less than 0°C) is projected to decline throughout the region.
- The number of crop-growing degree-days is projected to increase.
- Most areas within Auckland are projected to experience up to 2W/m² increase in solar radiation at the annual scale by 2110.

New Zealand’s mean temperature has increased by 0.9 degrees Celsius (°C) since the turn of the 20th Century (Stats NZ 2018). This upward trend in temperature is forecast to continue. By 2110, the mean annual temperature for the Auckland region is projected to increase by between 1.4°C and 3.3°C (Pearce et al., 2018). The amount of warming is not predicted to be the same throughout the region. Less warming is projected for the western areas and the greatest warming is forecast for the eastern areas. The season predicted to warm most is autumn elongating the summer season, whilst the seasons with the least warming are winter and spring (Pearce et al., 2018).

Mean daily maximum temperature (daytime temperature) and mean daily minimum temperature (night time temperatures) have both increased over the past few decades and this trend is also projected to continue. By 2110, yearly maximum (daytime) temperatures are projected to increase between 1.5°C and 3.75°C for much of the Auckland region, and annual minimum (night time) temperatures are projected to increase between 1.25°C between 3.5°C (Pearce et al., 2018).

2.1.2. Potential air quality impacts from predicted temperature and solar radiation changes

Summary of potential air quality impacts:

- Less wood burnt during winter in fireplaces due to warmer winters lowering wood smoke emissions.
- Multi-day pollutant build-up over the city with a possible heat dome and stagnant air pooling across urban areas.
- More photochemical reaction potentially increasing tropospheric ozone.
- Increase in mixing depth allowing for more dilution of air pollutants.
- Longer growing season for plants increasing pollen concentrations.
- Increased susceptibility to respiratory and cardio-vascular issues due to heat stress.

All RCP climate scenarios considered by NIWA show an increasing number of hot days across Auckland. Unusually hot or cold temperatures can negatively affect people’s health (Joynt 2018). Heat stress on the body makes people more susceptible to acute health problems that can be triggered by airborne pollutants such as nitrogen dioxide (NO_2) and fine particulate matter ($PM_{2.5}$) (Schwartz, Samet, and Patz 2004). For Auckland, NO_2 and $PM_{2.5}$ are largely emitted from anthropogenic (human-made) sources, with on-road transport being the major contributor (Davy et al., 2017). People are most likely to be exposed to these harmful pollutants when they are close to the emission source. Peak concentrations for these pollutants are identified close to or along roads (Longley et al., 2013). High temperatures tend to occur during periods of atmospheric high pressure, creating stable weather that results in airmass stagnation within urban centres through reduced airflow (ventilation). The pooling of air would allow pollutant concentrations to increase and change chemically (Jhun et al., 2015). Notable areas where highest concentrations could occur are next to heavily trafficked roads surrounded by tall buildings (Longely et al., 2014), areas with a large number of bus stops (Lim, Salmond, and Dirks 2015); and busy road junctions (Miskell 2013; Gómez-Baggethun et al., 2013).

Temperature has been found to play a large part in tropospheric ozone (O_3) formation. An Auckland study found that under now-typical summer conditions, O_3 concentrations were over 1.5 times higher than the general background (Adeeb, 2006). With solar radiation predicted to increase by up to 2W/m² (Pearce et al., 2018) O_3 concentrations are likely to increase in line with the findings from international research (Silva et al., 2017).

The contribution from wood smoke emitted during home heating across Auckland was estimated to account for 19 per cent of $PM_{2.5}$ and 11 per cent of the total PM_{10} mass averaged over eight years (Davy et al., 2017). Long-term exposure to wood or coal smoke is associated with non-accidental emergency department visits in the first three years of life. (Lai et al., 2017).

Home heating emissions are seasonal in nature so exact concentrations vary according to the location (Figure A1), season and temperature. Auckland's average winter temperatures are forecast to increase with frosts becoming rare except for high elevations in the Waitakere and Hunua ranges. Warmer winter nights should decrease the need for home heating through wood burning with commensurate reductions in particulate emissions.

Pollen are natural additions to air, and although not a pollutant, can have severe acute health repercussions for those sensitive to the spores when breathed in. It is by this mechanism that the pathway of exposure and the consequential health impacts are comparable to atmospheric pollutants, moreover, air pollutants can interact with pollen making them more potent (section 2.1.3). Therefore, this report will consider pollen as an airborne contaminant. It is projected that longer periods of warmer days will inevitably lead to a longer growth cycle for vegetation. This will, in turn, lead to an increased allergen season for Auckland (Knox et al., 1997).

2.1.3. How air pollution can make pollen more allergenic

Predicted increases in air temperature will allow for a longer growing season for plants. This could lead in increased concentrations of pollen in the atmosphere with detrimental health impacts for those that suffer allergic responses (Figure 2). Once in the atmosphere pollen can undergo physical changes that enhance its allergenic properties. When pollen is mixed with urban airborne pollutants, they can enact physiochemical reactions on pollen spores increasing the amount of proteins they contain. This increase in proteins enhances its allergenic properties (Bartra et al., 2007). Under the influence of high humidity, strong winds and ozone, airborne pollen can undergo a process called osmotic shock response, a chemical response within the pollen that fractures the spore into multiple micro-particles. These tiny particles (about 100 nm, the same size as the typical cold virus) become shrouded in micro-droplets of water that then condense upon aerosol particles in polluted air. The most common host particles are typically carbonaceous diesel particles due to their large surface areas (Knox et al., 1997). The carbon ‘core’ and the condensed pollutants coating the particle are easily inhaled deep into and through the lung system into the alveoli gas exchange network. It is by this inhalation process that asthma attacks and other acute respiratory disease symptoms may be triggered.

Increasing temperatures and longer warm seasons may give rise to increases in pollen as plants respond by advancing and prolonging their pollination period and increase their pollen output (Barnes et al., 2013).

Climate change may also lead to the extinction of some native species of plants and animals while allowing for the increased prevalence of non-native species. This could increase a subsequent risk of allergic sensitization to these new invasive species (Bartra et al., 2007).

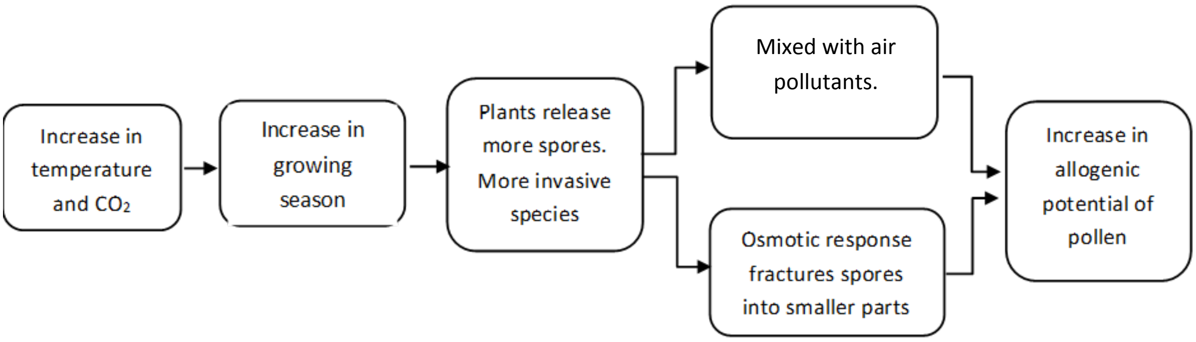

Figure 2 A system diagram describing the mechanisms by which climate change and air pollution can impact pollen spore’s allergenic potential.

Table 1 Evidence from current literature on the effects of temperature and solar radiation on air quality

Pollutant	Country or region	Climate change parameter	Impacts	Reference
Ozone (O_3)	USA	Temperature	Significant increases in O_3 and fine particulate matter ($PM_{2.5}$) in a multi city study. Linked with increasing temperature.	Jhun et al., 2015
	Global Modelling	Temperature and Sunshine	Increases in urban concentrations of O_3 expected due to increased photochemical reactions. Lower rural O_3 due to quicker water vapour destruction of O_3.	Silva et al., 2017
	Global	Temperature and humidity	Global increases in mortality from increases in urban O_3 triggered by increases in temperature and changes in humidity levels.	Schwartz, Samet, and Patz 2004
	New Zealand	Temperature and UV	O_3 pollution has been found to possibly reduce crop yields	Stevenson, Halley, and Noonan. 2000
Airborne particulate (PM_{10} / $PM_{2.5}$)	Taiwan	Temperature	Urban heat island changes urban thermal and dynamic meteorological processes in cities. Creation of thunderstorms and precipitation.	Lin et al., 2010
	Spain	Temperature changes	Air pollutants exert important actions upon aeroallergens. Pollen in heavily polluted areas interact with airborne particles can change pollen's structure facilitating their penetration of the human airways.	Bartra et al., 2007
All urban air pollutants	Global	Extreme temperatures	Changes in climate and air quality have a measurable impact not only on the morbidity but also the mortality of patients with asthma and other respiratory diseases.	D'Amato et al., 2015
VOCs	Global	Temperature	VOC emissions from vegetation shown to have strong dependence on temperature, with roughly a doubling of emissions per 4°C increase.	Guenther et al., 2006

2.2. Humidity and relative humidity changes

This section describes how the water vapour content of the atmosphere may interact with airborne particulate and gases as well as other airborne constituents such as pathogens and pollen. Climate change will change the water vapour content of Auckland's air (Section 2.2.1). The ramifications of these changes are considered in terms of air quality (Section 2.2.2).

2.2.1. Humidity and relative humidity climate predictions provided by NIWA

Summary of predicted changes:

- Most of the Auckland region experiences average annual relative humidity of between 80-90% per cent at 9am. Relative humidity is higher in winter than in summer.
- Auckland's annual relative humidity is projected to slightly decrease into the future.
- Absolute humidity is likely to increase with warmer air able to hold more moisture.
- Spring is the season that will experience the largest decreases in relative humidity.
- Small increases are projected for autumn.

Relative humidity (RH) is a measure of the relativity between current and possible future humidity levels. NIWA models a slight decrease across the region (Figure 3) (Pearce et al., 2018). However, absolute humidity levels (the total amount of water vapour the atmosphere can hold), will increase due to increased ambient temperature as warm air holds more moisture (Pearce et al., 2018). This increase in absolute humidity will impact in real terms as an oppressive feel to the atmosphere, like those conditions frequently experienced in recent summers under north-easterly air flows (a wind direction that traditionally brings hot humid air from the subtropical Pacific region).

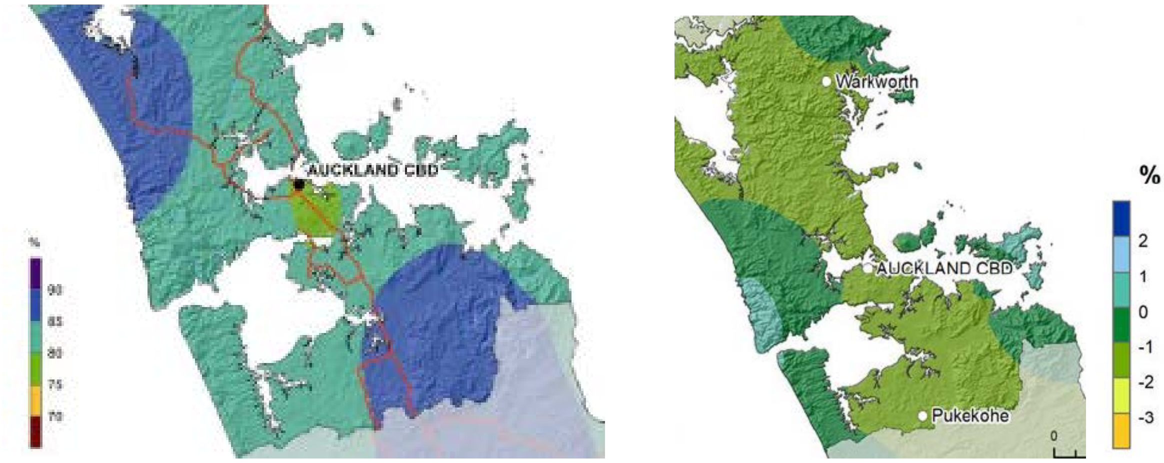

Figure 3 Current relative humidity levels (left) and future RCP 8.5 changes in relative humidity forecast for the Auckland region for the future period 2081-2100 (Pearce et al., 2018).

Current RH values are lower over the most urbanised areas of Auckland (Figure 3). The urban landscape generally has a lower water content than surrounding countryside due to the prevalence of concrete and other manmade materials, and less evapotranspiration. There is also increased heat over urban areas due to the fast-warming properties of concrete and road seal and its potential to retain heat longer than most natural substrates (Hass et al., 2016). It is likely that the RH levels may decrease away from coastal areas due to the joint effects of increased urbanisation and faster rates of temperature increase.

2.2.2. Potential air quality impacts from predicted humidity and relative humidity changes

Summary of potential air quality impacts:

- Increasing humidity may impact indoor air quality depending on ventilation methods.
- Increase in atmospheric water content may increase condensable surface areas that can transport viruses.
- Relative humidity can affect gas to particle conversion through vapour pressure properties across the particle surface. Lower RH would increase dissociation into the gas phase.
- Increased water content in dwellings may promote indoor mould growth.
- Increased atmospheric water content can lower airborne particle concentrations through mechanical processes.
- Humidity changes particle size modes depending on hydrophilic or hydrophobic properties of the chemical.

Humidity can affect air quality issues by changing the allergenic properties of certain pollens, making them more problematic to susceptible members of the population and increase the health burden on society through days off work and school with consequent reductions in productivity (Fann et al., 2016) (section 2.1.3).

Humidity also changes the nature of particulate matter in the atmosphere. The physical state of chemicals with low vapour pressure properties may change with increased humidity in the atmosphere. The vapour pressure point of particulates will be higher with increased humidity resulting in higher temperatures instigating semi-volatile species to dissociate to the gaseous state rather than bound as solid or aqueous particulates (Hinds 1982). This becomes important for understanding air pollution constituents and the associated risk potential to health.

Low and high humidity (water vapour) support transmission and survival of influenza viruses in many reported studies, but the relationship between temperature, humidity, viruses and aerosol dynamics is complex. Results reported by Wolkoff (2018) showed that the interaction between water vapour and airborne viruses is dependent on the individual virus type and its physiochemical properties.

Table 2 Evidence from current literature on the effects of humidity and relative humidity on air quality

Pollutant	Country	Climate change parameter	Impacts	Reference
O_3	Europe	Humidity and cloudiness	Daily peak and averaged O_3 concentrations substantially increase during summer in future due to higher humidity, temperatures, reduced cloudiness and precipitation.	Meleux, Solmon, and Giorgi, 2007
	Global	Humidity	Higher water vapour is predicted to decrease concentrations of background O_3 but increase urban O_3	Jacob and Winner, 2009
O_3, NO_2, $PM_{2.5}$	Global	Humidity and temperature	Hotter, more humid weather tends to irritate airways, making breathing more difficult for many people with asthma and other respiratory ailments.	Tibbetts, 2015
$PM_{2.5}$	USA	Humidity	Changes in humidity and cloudiness affect particulate concentrations (PM). Increasing relative humidity increases the PM water content and hence the uptake of semi-volatile components, mainly nitrate and possibly organics.	Dawson, Adams, and Pandis, 2007
Virus	Global	Humidity	Both low and high humidity favours transmission and survival of influenza virus.	Wolkoff, 2018
Aeroallergen	USA	Humidity	Humidity can make airborne pollens more problematic to sufferers, increasing health burden and implied costs through days off work and school.	Fann et al., 2016

2.3. Rainfall

Rainfall alters the amount and constituents of airborne pollutants over the urban atmosphere. With rainfall patterns predicted to change for the Auckland region (Section 2.3.1) it is expected that the make-up of air pollutants will also change. These changes are discussed with evidence considered from available research (Section 2.3.2).

2.3.1. Rainfall climate projections provided by NIWA

Summary of predicted changes:

- The number of rain days per year is projected to decline across the region. However, heavy rain days (more than 25mm of rain) are set to increase.
- An increased frequency of consecutive days with more than 40 mm of rainfall across Auckland is predicted.
- Extreme rainfall events are likely to increase in intensity in the Auckland Region due to a warmer atmosphere's capability of holding more moisture.
- The number of dry days (< 1mm of rain) per year is projected to increase.
- Potential evapotranspiration deficit (PED) is projected to increase throughout the region in the future. This means Auckland is likely to become more drought-prone.
- The number of days of soil moisture deficit is projected to increase.

Rainfall is predicted to fall more sporadically over the Auckland region. Spring rainfall is set to decrease, yet annual rainfall is set to increase (Pearce et al., 2018). The number of dry days is also set to increase, along with the number of heavy rain events; there is also a strong signal that the number of consecutive heavy rain days across Auckland will increase.

Extreme rainfall events that are considered rare today are likely to increase in number and intensity in the Auckland Region. This will be driven by a warmer atmosphere that has the capacity to hold more moisture. The magnitude of the 99th percentile of daily rainfall (the 1-2 wettest rain days of the year) is projected to increase across most of the region, by more than 25 per cent for south-east locations by 2110 (Pearce et al., 2018).

Potential evapotranspiration deficit (PED) is projected to increase throughout the region. The region will be more drought-prone, affecting soil moisture retention and plant growth. This will also have ramifications for relative humidity values in the few areas of Auckland that are away from large bodies of water.

2.3.2. Potential air quality impacts from predicted alterations in rainfall patterns

Summary of potential air quality impacts:

- Longer drier periods may enable air pollutants to accumulate through less wet deposition.
- Longer periods of drought promote plant stress which can increase the release of volatile organic compounds (VOCs).
- Increases in volatile organic compounds could increase tropospheric ozone concentrations with consequential effects on urban NO_2 concentrations.

Rainfall acts to remove particulate from the atmosphere through a process called wet deposition. Rainfall can help wash airborne dust and dirt particulates out of the atmosphere. The regularity of rainfall was reported to be more important than rainfall intensity as a mechanism of removing atmospheric pollutants (Tai et al., 2012). For Auckland, the more sporadic rainfall predicted would be less efficient at removing particulates from the atmosphere increasing atmospheric concentrations, and exposure to these pollutants by the populace. The effectiveness of this removal process is also dependent on the altitude of the cloud, size of the rain droplets, and the diameter and concentration of the particulates in the atmosphere (Riebeek, 2006). Periods of lower rainfall or no rain would allow pollutant levels to escalate. Conversely, more rainfall can cause behaviour/mode share change that increases particulate concentrations (Kwak et al., 2017). Rapid coagulation of fresh vehicle emissions would enhance accumulation-mode size particles consisting of aged vehicle exhaust with a smaller component of sulphate from sources such as the surrounding oceans and emissions from volcanic activities.

Increasingly sporadic rainfall may allow the accumulation of pollutants on road surfaces. Typical sources of on-road pollutants are metals from catalytic converters, rubber from tyre wear and tear and accumulate from vehicle mechanisms. In the absence of rainfall that would effectively wash the road surfaces, these sources, such particulates could be resuspended within road dust, primarily alongside busy roads. Road dust is already an issue along unsealed roads across the Auckland region (Bluett et al., 2017).

There are numerous reports of anomalously large and numerous forest fires world-wide. The summer of 2018 over the northern hemisphere was especially hot and dry over vast areas of continental Europe, Russia and North America (Daisy and McSweeney, 2018). Although there are many factors that can cause forest fires, climate change has been found to be a prominent influence. Moreover, climate models project that wildfire potential will increase world-wide as rainfall patterns change due to climate change (Liu, Stanturf, and Goodrick., 2010). With drier conditions forecast for Auckland (Pearce et al., 2018), forests such as the Waitākere Ranges may also become more vulnerable to fire (Pearce et al., 2011). Forest fires over the Waitākere Ranges would cause large plumes of carbonaceous particulate and gas to be emitted with the potential to seriously affect Auckland's air quality.

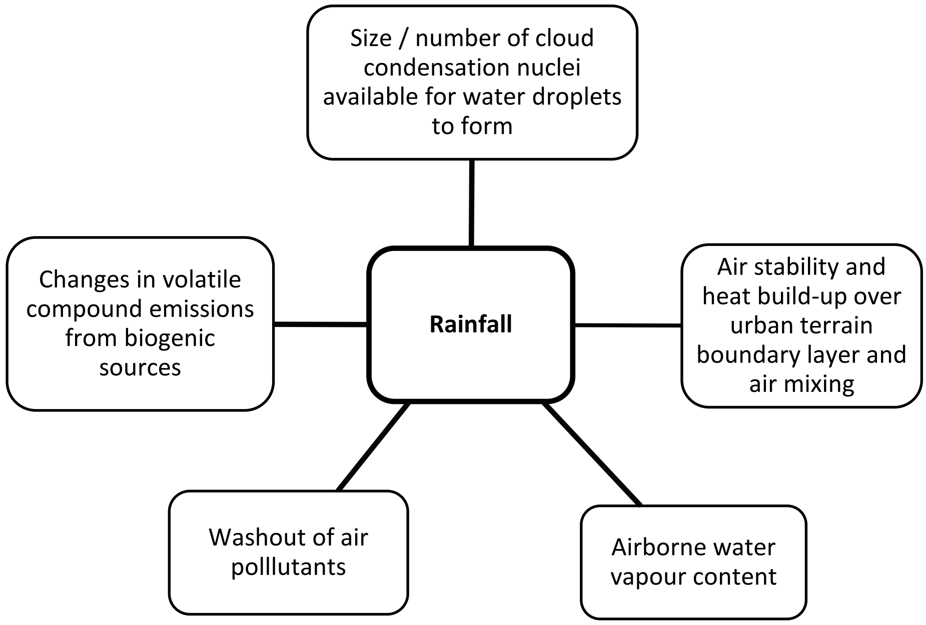

Figure 4 Diagrammatical description of the ways in which air quality might be affected by changes in rainfall.

During heavy rainfall events these pollutants will leach into the surrounding soils and run-off into waterways, polluting the surrounding land. Rain also acts to moderate temperature. Extended periods without rainfall may exacerbate temperature increases, especially around urban centres due to the previously described heat potential of urban structures and materials. During dry periods there would likely be a lowering of relative humidity due to evapotranspiration water deficit. As a result, there is likely to be an increase in particulate concentrations through increased photochemical reactions of air pollutants. Abiotic stress factors also affect plants by creating stress conditions. It is widely reported that stress conditions such as water and nutrient scarcity increase the release of volatile organic compounds (VOCs) from plants (Section 2.3.4). A key stress for plants is the unavailability of water and nutrients in times of drought; hence changes in rainfall patterns might increase VOC release increasing NO_2 concentrations via O_3 and photolysis pathways.

2.3.3. How plant stress caused by increasingly sporadic rainfall patterns may increase ozone concentrations over Auckland

Plants and trees such as those found in the Waitākere Ranges emit various biogenic volatile organic compounds (VOCs) (Karl et al., 2009). VOCs are compounds that have low vapour pressure properties and are highly reactive. When under abiotic and biotic stress plants release more VOCs (Zhao et al., 2017). VOCs can undergo complex reactions with NO_x species (typically released by vehicle exhaust) and driven by photo oxidation from sunlight (Finlayson-Pitts and Pitts, 1993). These reactions together can form ozone. There are two prominent mechanisms by which plants release more VOCs into the atmosphere. Firstly, a warmer environment would lower the vapour pressure point for many key VOCs, enhancing their emission rate (Guenther et al., 2006). Secondly, plants release VOCs such as isoprene, monoterpenes and sesquiterpenes as a method to mitigate harmful oxidation processes within the leaf cells that would otherwise damage photosynthetic capacity of the plants (Zhao et al., 2017). This second process would likely increase as rainfall patterns change with longer dry interludes and heat exacerbating plant stress. To date, VOC emission rates from forests surrounding Auckland are not well understood. Future changes in naturally emitted VOCs should be measured to better understand how these biogenic emissions impact on harmful NO_2 concentration trends in Auckland.

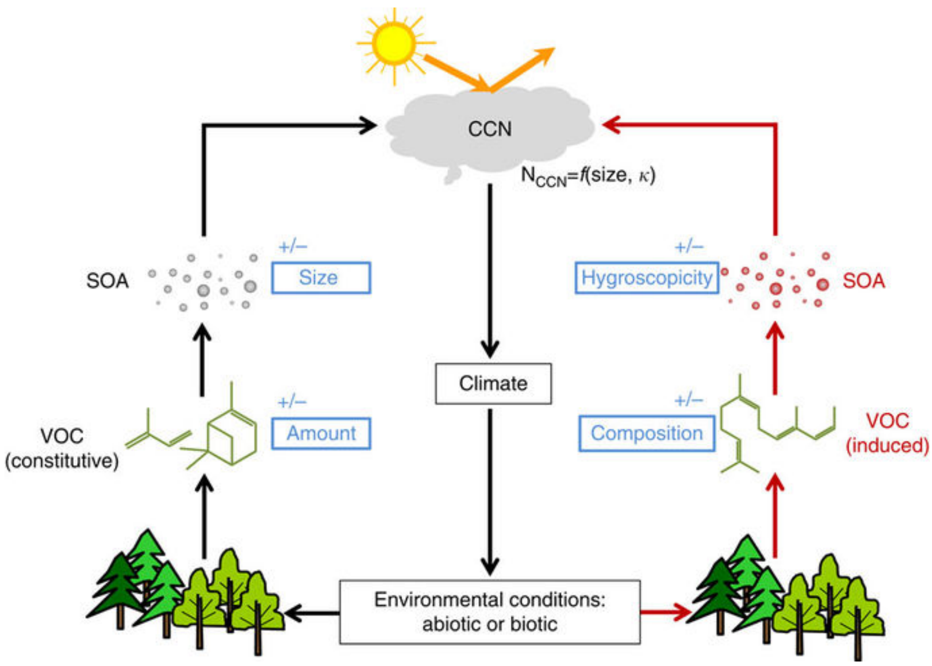

Figure 5 Schematic of the interaction between atmosphere, volatile organic compound release from plants and formation of secondary organic aerosols (SOA) (Zhao et al., 2017)

Table 3 Evidence from current literature on the effects of **rainfall** on air quality

Pollutant	City or Region	Climate change parameter	Impacts	Reference
Urban air pollutants	Global	Rainfall	More rain can occur when the bubble of heated air forms over very warm urban areas. Heated air rises faster and climbs higher over cities. The tiny water droplets turn to ice, during this process water molecules must release heat, adding energy, pushing particles yet higher. Ultimately increasing rain intensity.	Riebeek 2006
$PM_{2.5}$, PM_{10} and O_3	Korea	Rainfall	Rainfall found to have opposing effects on air pollutants in Seoul. Rainfall 'washes' modest amounts of particulates out the air. However, increase traffic volume during rain increases concentrations of NO_2 and $PM_{2.5}$ pollution levels.	Kwak et al., 2017
	USA	Rainfall	Elevated O_3 and $PM_{2.5}$ attributed to the combined effects of drought on deposition, natural emissions (wildfires, biogenic volatile organic compounds (BVOCs), and dust), and chemistry.	Wang et al., 2017
Carbonaceous particles	USA	Rainfall and temperature	Fire risks were found to be strongly associated with increased spring and summer temperatures as well as a drying trend caused by changes in global circulation.	Liu, Stanturf, and Goodrick 2010

2.4. Wind speed, direction and atmospheric pressure

Wind speed and direction largely dictate the amount and origin of air pollutants. Traditionally, Auckland's air is diluted by a reliable south-westerly wind from the relatively unpolluted air of the Southern Ocean. However, this is predicted to change (Section 2.4.1). Changes in wind speed and direction may have implications for air pollution levels across Auckland, such changes are set in context of reported findings elsewhere.

2.4.1. Wind speed, direction and atmospheric predictions provided by NIWA

Summary of predicted changes:

- More anticyclonic patterns (high pressure) predicted for Auckland.
- Mean annual wind speeds are projected to decrease.

- A reduction in mean sea level pressure in winter may increase winter wind speeds.
- The number of windy days (greater than 10 m/s) will continue to decline.
- North-easterly air flows will become more common for Auckland.
- Ex-tropical cyclones that approach Auckland in the future may retain more tropical characteristics including their strength.

Climate projections describe an overall increase in surface atmospheric pressure over Auckland (Pearce et al., 2018). The largest increases in pressure are forecast to the south of New Zealand, which would increase the occurrences of north-easterly flows over the Auckland region.

The mean wind speed has been rapidly declining for the past few decades (Figure 6). NIWA associated the observed decrease in wind speed to long-term trends in the Southern Annular Mode, which has a complex interrelationship with stratospheric ozone depletion and greenhouse gas increases (Pearce et al., 2018). This decreasing trend is forecast to continue at a slower rate.

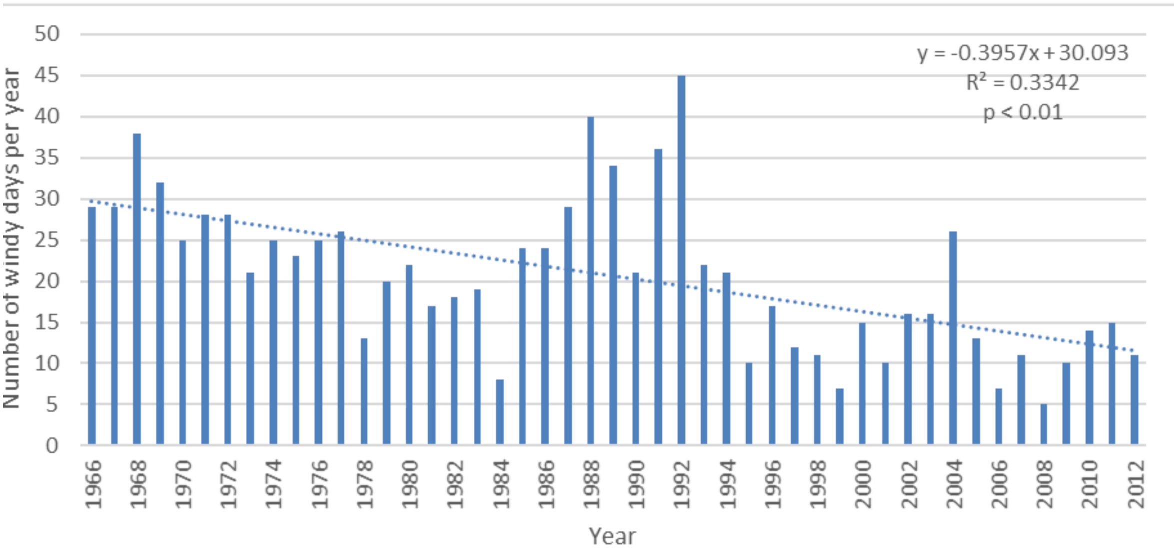

Figure 6 Annual number of windy days (mean daily wind speed >10m/s) for Auckland Airport, 1966-2012. Trend indicates a decrease in the annual number of windy days of approximately four days per decade (Pearce et al., 2018).

2.4.2. Air quality impacts from wind speed predictions

Summary of potential air quality impacts:

- Lower wind speeds would decrease the sea salt contribution to Auckland's air with greatest impacts on PM_{10} concentrations.
- Decrease in wind speeds could reduce upper level atmospheric mixing, allowing for increasing concentrations of air pollutants to build-up in locations with prominent emission sources.

- Windier conditions projected for the winter seasons would reduce the chance of colder nights and reduce the likelihood of brown haze air pollution events.
- Lower overall wind speeds could permit localised increased concentrations of air pollutants in pollution hotspots.

Research carried out in North America found that lower wind speed along with higher temperature and relative humidity were correlated with increased $PM_{2.5}$ concentrations (Tai et al., 2012). These results have been corroborated by Cheng and Lam (1998) who found wind speed and direction to be highly correlated to SO_2 and total suspended particle (TSP) concentrations in their analysis of long term trends in Hong Kong. Reduction in particle mass was reported by during synoptic scale cyclonic conditions through the reduction of entrained sea salt contribution (Kim et al., 2017). Aerosol plumes can be entrained in cyclonic weather fronts and travel large distances. Decreasing local winds may act to reduce dispersion of locally emitted pollution.

Placing these results in an Auckland context, the predicted reduction in wind speed and changing wind direction from a south-westerly to north-easterly flow will modify the aerosol loading from sea salt across the Auckland region. Oceanic marine aerosol such as sea salt typically originates from off the south-east coast of Tasmania and off the north-east coast of New Zealand (Figure 7).

The lowering of wind speeds would increase dry deposition rates of larger particulates in a process called gravitational settling (Hinds 1982). This would effectively reduce the number of large airborne particles helping to lower PM_{10} concentrations across the Auckland region. Both the reduction in sea salt contribution and in the larger “coarse mode” suspended particulate are important changes to consider in terms of Auckland meeting its National Environmental Standard and regional air quality targets. The benefits to society from such reductions would be minimal due to the largely benign health impacts from sea salt and the inability of coarse particulates to travel deep into the lungs

Wind speed and direction have been found to be crucial factors in the development of brown haze events that can appear over Auckland during winter mornings. Still conditions are the precursor for temperature inversions that can trap pollutants close to the ground (Salmond et al., 2016). The predicted reduction in wind speed may counter the expected increase in winter temperatures. It could be expected that despite the reduced influence of relatively warm sea during winters nights, temperatures will still fall low enough for temperature inversions to form close to the ground, allowing brown haze events to continue to form (Salmond et al., 2016). Dirks et al., (2017) reports a statistical link between Auckland’s brown haze events, high ground level air pollution, and increase in hospital admission for respiratory admissions.

A north-easterly flow may also increase the contribution of shipping emissions over Auckland. With Auckland's major port and shipping lanes located to the north-east of the city, there is an increase in SO_2 and certain metals associated with the heavy diesel fuel used by shipping when the wind comes from the north-east sector (Talbot et al., 2017). These increases have been most evident close to the port in Auckland's densely populated city centre.

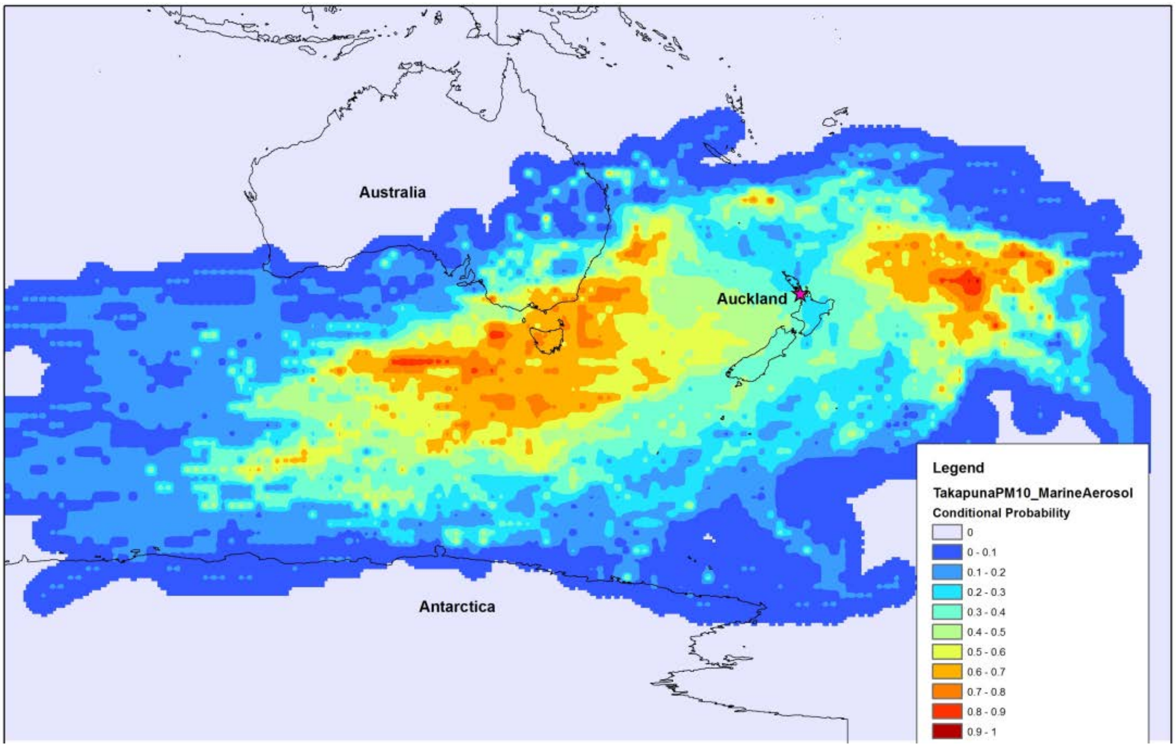

Figure 7 A probability source contribution function plot for the Takapuna PM_{10} marine aerosol source contribution data showing that the most likely source regions are in the Southern Ocean below Australia and Pacific Ocean to the north-east of Auckland (Davy et al., 2017).

Table 4 Evidence from current literature on the effects of wind speed direction and atmospheric pressure on air quality.

Pollutant	**City or region**	**Climate change parameter**	**Impacts**	**Reference**
$PM_{2.5}$ and PM_{10}	Europe	Wind speed	Decreasing wind speed increases $PM_{2.5}$ due to changes in dispersion and dry deposition. Wind speed dramatically affected sea salt emissions within $PM_{2.5}$ size fraction in coastal areas.	Megaritis et al., 2014
	Portugal	Wind speed and boundary layer depth	Increase in PM_{10} concentrations during specific months explained by the average reduction of the boundary layer height and wind speed.	Carvalho et al., 2010
NO_2 and PMx	New Zealand	Wind speed and temperature	Calm wind conditions were correlated with brown haze events in Auckland winter days. The results show that haze is observed during weekday mornings in the cool months,	Salmond et al., 2016
All urban pollutants	Egypt	Wind speed and humidity	Traffic pollutants were highest when wind speed was low. At higher wind speeds, large particles were entrained by the wind, thus contributing to ambient particulate matter levels. Average concentration for NO_2 and O_3 occurred at humidity over 40% indicative for strong vertical mixing.	Elminir 2005

3. Social and landscape factors influencing air pollution impacts

Air pollutants are a significant trigger of acute health impacts in exposed and vulnerable communities (Harlan and Ruddell, 2011; Hales et al., 2012). They can also have an indirect impact by limiting the ability of different groups to adjust or mitigate against air pollution impacts (Bennett et al., 2015 Calderón-Garcidueñas et al., 2008; Barnes et al., 2013). In many areas of Auckland, socio-economic factors overlap with exposure to poor air quality meaning that climate change will likely further enhance current social inequities. As air pollution dynamics change in response to climate change, there is likely to be an increase in the number of Aucklanders whom will experience negative health impacts. Public health research both globally and in New Zealand shows that the negative impacts of air pollution are already inequitably distributed (Pearce and Kingham, 2008; Pearce et al., 2006; Kjellstrom et al., 2007) and that this is likely to continue with the impacts of climate change (Patz et al., 2007). This means it is important to identify factors that directly and indirectly influence susceptibility to, and health impacts of, air pollutants.

This section highlights two high level factors that will contribute to climate change-enhanced air pollution impacting on communities already struggling with this issue. Social determinants have been identified in the literature as significant, alongside geographical determinants. While these have been separated for the purposes of this overview, future research is needed to explore how these works together to impact particular communities. This identification and assessment of the uneven socio-geographic impacts of climate change-enhanced air pollution can support communities, decision-makers and stakeholders to develop monitoring and mitigation strategies.

For example, communities with low employment rates may also have a large population of 5-14 year olds, and poor health outcomes (section 3.2 and 3.3). These communities may also live in close proximity to busy roads increasing their exposure to vehicle emissions (Longley et al., 2013). As such, all the factors described below may have a bearing on how climate change impacts Auckland's diverse communities. These disparities are likely to be enhanced as climate change intensifies the impacts of air pollution on these communities.

Two important caveats are that 1) there are many modes of exposure to air pollutants, and 2). communities are not static; commuting and workplace exposure to pollutants (school, kindergarten or business) have all been identified as important factors in a person's daily exposure to hazardous air (Alvarez-Pedrerol et al., 2017; Dirks et al., 2012).

3.1. Social factors

Social factors have been identified as contributing to the inequitable exposure to air pollutants. As climate change enhances the impacts of air pollution, it should be expected that these communities will be even more at risk, especially where these social factors overlap, including with geographical features discussed below.

3.1.1. Age and ethnicity

Age has been shown to be a significant factor in terms of the health impacts of air pollution, and particular age groups are likely to experience these more deeply with climate change. Young and aging communities in particular have more acute responses to air pollutants. Children have higher respiratory rates than adults, meaning they are more susceptible to inhaling pollutants, while also having less developed immune responses (Dirks et al., 2017). Elderly people tend to have more chronic disease, which can enhance the harmful effects of air pollution. Older people may also have weakened immune response to air pollution (Rivas et al., 2014).

Relatively small increases in air pollutants can impact disproportionately the young and elderly residents of Auckland (Dirks et al., 2017; Kuschel et al., 2012). International studies have supported these findings, providing strong evidence that gases such as SO_2 and NO_2 and fine particulates ($PM_{2.5}$) released primarily from on-road vehicles, are a major cause of acute health impacts on the elderly (Simoni et al., 2015) and the young (Gehring et al., 2002; Gilliland et al., 1999). The young and elderly within Auckland's communities are known to be susceptible to negative health outcomes like acute respiratory and cardiovascular ailments. These can be aggravated with pollutants commonly emitted from sources including on-road vehicles including NO_2, O_3 and $PM_{2.5}$, and which may be enhanced by climate change.

Similarly, some ethnic groups may be more exposed to air pollutants than others due to pre-existing social inequities. This over-exposure means that some ethnic groups having higher rates of most major diseases, such as cardiovascular and chronic respiratory disease, as well as experiencing poorer access to, and quality of, healthcare (Jones et al., 2014). There is a notable overlap when comparing communities with disproportionately poor health and those communities with large Māori populations. These results are in agreement with the findings from the Auckland District Health Board (Hales et al., 2012).

For example, asthma is the most common respiratory disorder in New Zealand with 1 in 4 people known to be afflicted. Although asthma sufferers are equitably distributed across all ethnicities, research has highlighted that Māori and Pacific communities suffer disproportionate hospital admission rates for respiratory disorders such as asthma and cardio-vascular disease (Barnard and Zhang., 2016).

3.1.2. Pre-existing health patterns

Air quality has greater impacts for those who suffer from respiratory disorders. (Barnes et al., 2013). Communities with higher rates of hospitalisation from respiratory, pneumonia and chronic obstructive pulmonary disease have enhanced susceptibility to the health impacts of poor air quality (Barnard and Zhang, 2017, Bennett et al., 2015). Beasley et al. (2016) found that one in three children and one in six adults suffer from asthma in Auckland, with an even distribution of sufferers across the region. However, the number of severe asthma or respiratory cases disproportionately affects certain groups, with correlations to poor quality housing (Bennett et al., 2015), poor access to healthcare (Horsburgh and Norris., 2013), low income (Hodas et al., 2012), ethnicity, (Jones et al., 2014), and age (Rivas et al., 2014, Simoni et al., 2015).

Exacerbation of previous health issues (acute impacts) are now a well reported effect of exposure to common air pollutants such as O_3 and NO_2 (Gehring et al., 2002; Cames M and Helmers, 2013). These impacts can also include increased susceptibility to flu (Huang et al., 2016) and allergens (section 2.1.3). More water vapour in the air can mean increased humidity and more potential for mould. Poor housing stock and ventilation issues will exacerbate these issues. Similarly, an increase in tropospheric ozone can affect people with existing respiratory or cardiovascular disease over areas with high traffic or other VOC sources.

3.1.3. Adaptive capacity

Adaptive capacity refers to how communities can change in ways that protect themselves against increases in air pollution and its health impacts. Income, housing and employment have been identified as significant proxies for adaptive capacities to worsening air pollution (Jones et al., 2014, Hodas et al., 2012). Housing in particular will be significant as the ability for households to adapt the ways their homes to manage increased heat and moisture levels will impact the wellbeing of those households. Exposure will be reduced or increased according to each householder’s ability to access affordable mechanical cooling of their residence during warmer summers, protection from roadside pollutants, and clean source of heating and adequate healthcare.

Housing quality and design also impact exposure to air pollution. An increase in the temperature and the water content of the air, as well as an increase in hot days should see a reduction in wood smoke emissions from home heating (Section 2) and improved air quality within the home through lower wood smoke emissions. However, these same increases will likely increase the need for atmospheric controls within dwellings. Good mechanical ventilation, as well as methods to control temperature, will become more important for comfort as well as to reduce the risks of mould from damp conditions. These systems come at a cost that low income households, and/or renters will struggle to afford. Furthermore, if housing ventilation occurs largely through opening windows, then proximity to roads will become more important as pollutants from road traffic can accumulate indoors and remain for extended periods (Talbot et al., 2017). Warmer winters may help reduce the need for wintertime wood burning, lowering emissions. However, the need for cooling house interiors increases with a warmer Auckland.

3.2. Landscape factors

The land-use, geography and topography of Auckland's landscapes will also play a role in the differential exposure of Auckland communities to climate change-enhanced air pollutants. This includes the influence of built forms and natural forms.

3.2.1. Urban development

Communities in close proximity to major roads and motorways are exposed to a major source of NO_2. This is a particular concern in instances where schools or residential homes for elderly people are within 50m of major arterial routes. Notably, NO_2 has the potential to increase with climate change, as O_3 increases with more sunshine, higher temperature and lower wind speeds. Research carried out in Auckland has identified that areas where there are large numbers of bus stops close to road junctions have high concentrations of vehicle emitted pollutants (Lim et al., 2015; Miskell 2013); this is also supported by international research (Moreno et al., 2015).

Infrastructural and zoning features that can contribute to the uneven social impact of air pollution are proximity to busy arterial routes, proximity to commercial/industrial zones, and housing quality and typology. Increased concentrations are more likely to occur in areas with reduced dilution and outflow, such as high traffic routes, street canyons and/or busy intersections in built up areas with tall buildings (Lim et al., 2015).

In Auckland, the intensification of existing urban areas are designed with support for low carbon mobility and public transport options, reducing the need for greenfield development (Auckland Council 2016). However, if these low-pollutant design options are not implemented, the increasing traffic volume and reduced traffic flow may increase the health impacts of air pollutants. (Liu et al., 2017). Taller buildings can also increase air pollution concentrations by limiting dilution as lower wind speeds will reduce dispersion of particulate away from areas of high emissions, allowing build-up of pollutants (Aristodemou et al., 2018).

A further feature of intensification that may expose Auckland's communities to air pollutants are areas where unitary plan zones enable mixing of retail and industrial activities. Both large-scale retail and industry rely on delivery vehicles, potentially increasing harmful diesel emissions in the area. Evidence of industrial emission sources is available through source apportionment measurements carried out in Takapuna (Davy et al., 2017) and emission inventory data (Grange et al., 2015). One mitigating factor may be that coastal locations are known to receive a reliable clean sea breeze diluting and dispersing airborne pollutant concentrations (Steyn, 1996).

3.2.2. Local geographic features

The heating and cooling requirements of houses will also be impacted by the location they are in. For example, exposure to air pollution may be exacerbated by high wood use for home heating and poor dispersion caused by valley topography. This may be further enhanced if the dwelling is in an urban valley but may be decreased if near the coast. Furthermore, as temperatures increase and wind speed decrease, the air could have time to stagnate allowing pollution levels to increase in certain hotspots. As stated, heat-related health consequences increase as air quality degrades (Harlan and Ruddell, 2011; Joynt, 2018).

4. Conclusion

Air quality impacts resulting from climate change are identified by extracting current findings from local and international literature. Four meteorological parameters were considered including wind speed and direction, temperature, humidity and rainfall. All were identified as having dependent and inter-dependent impacts on air quality and are predicted to change in future climate scenarios. This report sets these possible impacts in the context of current air quality conditions and environment across Auckland. These include possible emissions reductions from woodburning from home heating with night time warming. Lower dispersal of pollution in lighter winds. More secondary pollutants forming from hotter, sunnier conditions and possible increases of biogenic VOCs that may result in increased ozone concentrations. The report also details how the allergenic properties of pollen might become enhanced in conditions which favour high humidity, strong winds and ozone. Increased forest fire activities in neighbouring wooded areas may also have notable detrimental air quality impacts for Auckland.

Social and landscape factors that are known to have independent and interrelated impacts on communities are considered. Age and ethnicity, those with pre-existing health problems, local geographic features and urban development factors are all assessed independently. Current knowledge is used to investigate how these factors might negatively impact household and communities across Auckland.

This report offers a starting point for stakeholders to identify social and geographical factors where monitoring, mitigation and support networks could be prioritised. This report creates a pathway for future research to focus on location-based research to identify communities with disproportionate numbers of those at risk.

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